DEVELOPMENT AND VALIDATION OF EYE INJURY AND FACIAL FRACTURE CRITERIA FOR THE FOCUS HEADFORM

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ABSTRACT

A multi-year research effort focused on predicting eye and face injury resulting from blunt impacts has been completed through a collaborative partnership of Virginia Tech – Wake Forest, Center for Injury Biomechanics, Denton, and the United States Army Aeromedical Research Laboratory. The primary goal of this effort is the development and validation of a physical headform capable of measuring face and eye impact loads. In order to assess the capability of protective equipment in reducing eye and facial injuries, this innovative advanced headform has been developed to predict injury. Because of the headform's emphasis on eye and orbital injuries, the new advanced headform is dubbed the Facial and Ocular CountermeasUre Safety headform. A two-part study has developed and validated a biofidelic headform (FOCUS) with corresponding injury criteria for globe rupture and facial fracture.

1. INTRODUCTION

Injuries to the face and eye can be seriously debilitating or fatal and will dramatically reduce the combat effectiveness of the American soldier. The rate of eye injuries has dramatically increased in warfare from approximately 2% during World War I and World War II, to nearly 13% during Operation Desert Storm (Heier 1993, Wong 2000). Current estimates show a nearly 4:1 ratio of injuries to the eye and face compared to the thorax. In order to assess the capability of protective equipment in reducing eye and facial injuries, an innovative advanced headform has been developed that can predict fracture of facial bones, as well as eye injury from impact loading (Kennedy 2006A, Kennedy 2007) (Figure 1). This paper will detail the development and validation of a biofidelic eye and eye injury criteria for globe rupture and facial fracture thresholds, that allow interpretation of FOCUS data and application to real world combat injury prevention scenarios.

Figure 1: The FOCUS headform is designed to predict the risk of eye and facial injuries.

2. METHODS

The FOCUS headform was developed at the Virginia Tech–Wake Forest, Center for Injury Biomechanics, in conjunction with Denton ATD, Inc. and input from the United States Army Aeromedical Research Laboratory (USAARL). The exterior geometry of the headform matches the anthropometry of a 50th percentile male soldier, developed by USAARL which allows helmets

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and other headgear to fit more precisely than other ATD headforms. The internal structures of this headform were designed to accommodate the specific sensor requirements while maintaining the mass and inertial properties necessary for biofidelic response of the head to impact loading (Kennedy 2006A).

Using the FOCUS headform, a two-part study developed and validated the biofidelic headform with corresponding injury criteria for globe rupture and facial fracture. The FOCUS synthetic eye was developed to match the force-deflection response of human eyes in-situ. Experimental eye impact tests were conducted using the FOCUS headform and were correlated to eye impact data reported in the literature (Kennedy 2006B, Kennedy 2007) (Figure 2). To determine injury criteria for the facial bones, impacts were performed with an instrumented cylindrical rod in the longitudinal direction using a free-falling mass onto the facial bones. Facial fracture tolerances for 50% risk of injury were found for the frontal bone, nasal bone, zygoma, maxilla and mandible.

2.1 Synthetic Eye Development

The FOCUS headform has been designed with discrete load cells capable of measuring local impact forces to predict ocular injuries (Figure 3). In order to develop a biofidelic eye and orbit assembly the force-deflection response was determined and compared to the results from *in-situ* impact tests.

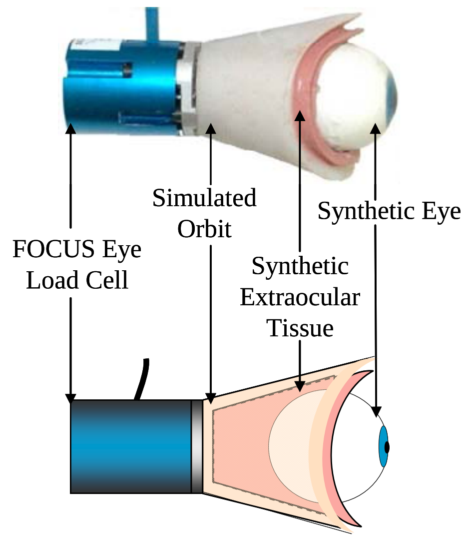

Figure 3: Schematic of the synthetic eye and instrumentation arrangement used in the FOCUS headform.

Human eyes were tested to characterize the force-deflection response of the eyes under blunt impact, and then a urethane synthetic eye was tested for comparison. All tests were conducted using a spring powered impactor at approximately 10 m/s (Figure 4) and the force-deflection response for *ex-vivo* human eyes as well as synthetic eyes were determined.

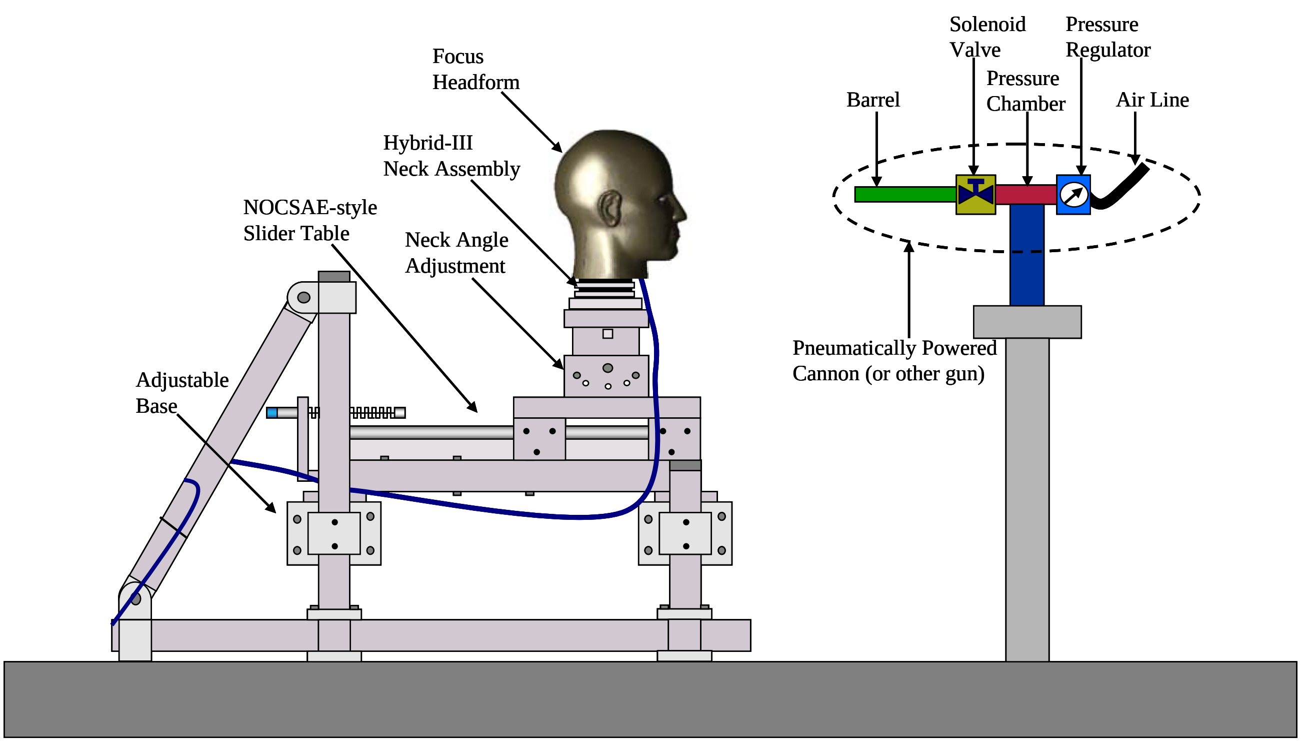

Figure 2: Experimental test configuration with the FOCUS headform.

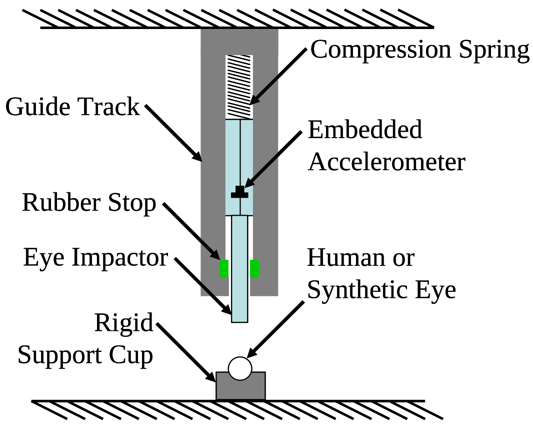

Figure 4: Spring-powered impactor setup to measure force-deflection.

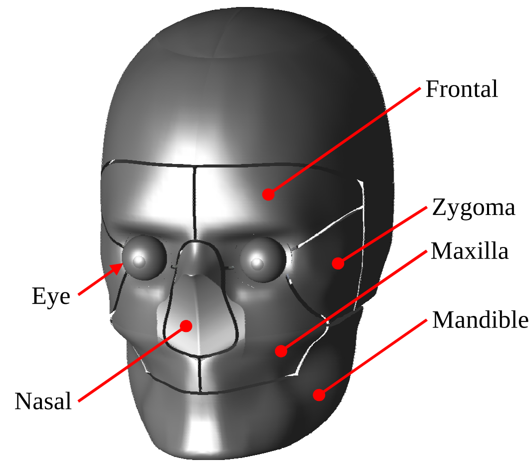

Figure 5: Segmentation of instrumented FOCUS headform.

Then force-deflection response of the *in-situ* human eye was determined based on impact tests on human cadavers. This data was used to test different modular orbit designs for the FOCUS headform and select materials based on the most biofidelic response possible. Experimental eye impact tests were performed using the FOCUS headform. These impact tests corresponded to eye impact data reported in the literature and the injury outcome from those experimental tests were correlated to the output of the FOCUS headform. This data was used to generate injury risk functions for globe rupture specific to the FOCUS headform.

2.2 Facial Fracture Injury Tolerance Development

In order to assess the severity of blows to various regions of the face, the skull is segmented into various sensing areas consistent with the anthropometric regions of the human skull. Five facial bones are monitored for injury with the frontal, zygoma, and maxilla monitored separately on left and right sides, and the nasal and mandible monitored as individual regions with no distinction between left and right sides (Figure 5). The headform consists of an outer layer of molded skin, with material properties consistent in thickness and force-deflection response to actual skin, and an underlying rigid skull. Average facial skin thickness was taken from previously published studies of facial skin thickness (Phillips 1996).

The facial fracture injury thresholds were determined using a total of 92 tests performed on 14 unembalmed human heads, along with previously published data. A 7 lb cylindrical impactor was used to apply the impact to each of the facial bones (Figure 6). The impactor was dropped from a height of 5 cm to 190 cm to produce a range of impact forces and struck the face with a velocity of 1 m/s to 6 m/s. The impacting surface had an area of 1 in^2 and was machined with a slight bevel around its surface to reduce edge effects. Each head was instrumented with two Acoustic Emission (AE) sensors (Micro30S, Physical Instruments, New Jersey) mounted to the mandible and to the frontal bone just posterior to the apex of the forehead.

To take advantage of the previous work, the data given in each study was placed into a database along with pertinent descriptors of each test method. To estimate risk of fracture as a function of force, a survival analysis was performed utilizing parametric and non-parametric techniques. For the parametric analysis, a Weibull model was assumed and was fitted to the fracture data. A non-parametric model was created using the Consistent Threshold (CT) method described by Nusholtz and Mosier (1999). From the statistical analysis of the current data and similar previously performed tests the facial fracture thresholds were determined.

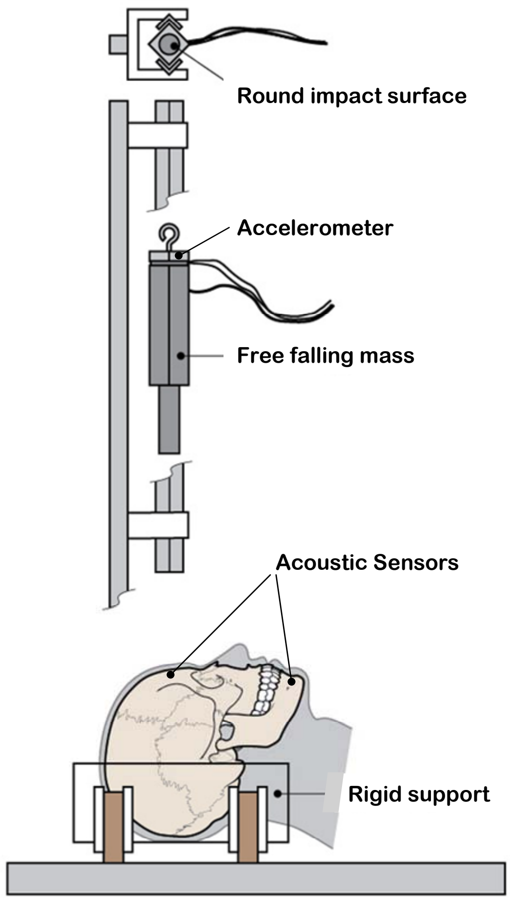

Figure 6: Schematic of test apparatus used in the current study.

3. RESULTS AND CRITERIA

3.1 Injury Risk Criteria for Globe Rupture

The force-deflection response of the synthetic orbit assembly was determined and compared to *in-situ* impact tests of the human eye. The response of the system for three impacts is plotted against the corridors developed for the force-deflection of human eyes *in-situ* (Figure 7). The response can be seen to fall entirely within the corridors to the cutoff at 7.5 mm and, as such, was determined to be representative of human eye response to dynamic impact because this is where globe rupture is typically observed (Kennedy 2006).

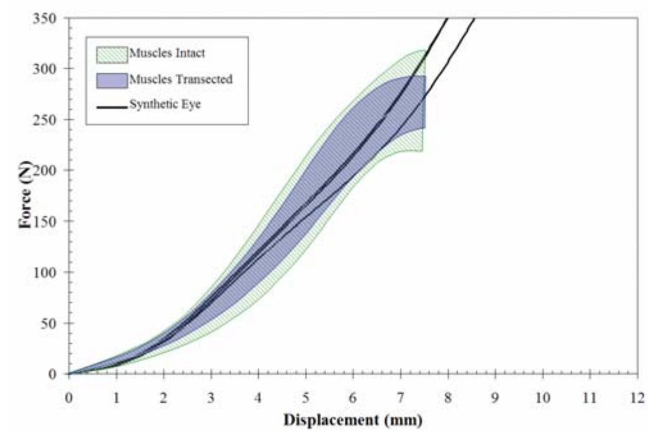

Figure 7: Force-deflection results from impacts performed on a simulated orbit with a urethane synthetic eye and silicone synthetic extraocular tissue.

A risk function using the generalized logistic regression equation was fit between peak force and risk of globe rupture based on normalized energy of the impacting BB. Using peak force as a predictor of injury, the coefficients for the injury risk function were determined and the risk function developed as shown (Figure 8). A 50% risk of globe rupture from a 4.5 mm BB impact is determined to result from a measured 107 N peak impact force ($R^2 = 0.995$).

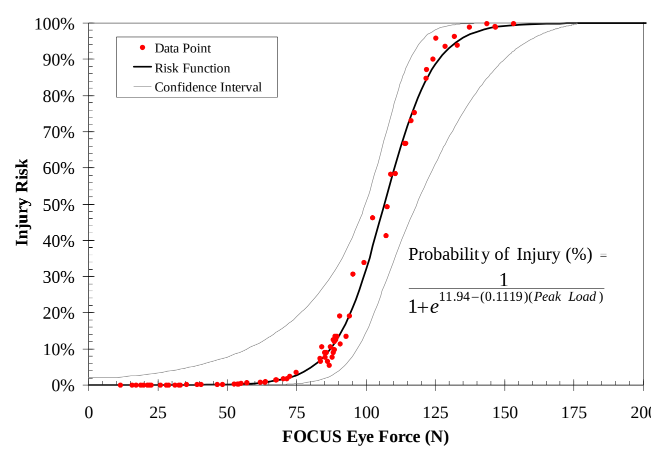

Figure 8: Injury risk curves for globe rupture with confidence intervals calculated from peak force of FOCUS eye load cells.

Given the significance of the normalized energy in predicting globe rupture (Kennedy 2006), a risk function using the generalized logistic regression equation (shown in Figure 8) was fit between peak force and risk of globe rupture based on normalized energy of the impacting BB. A risk function of this form can be used to determine the probability of sustaining globe rupture based on the impact force measured by the FOCUS headform. A 50% risk of globe rupture is shown to be 107 N (Figure 8).

3.2 Injury Thresholds for Facial Fracture

The provisional thresholds for the frontal bone, nasal bone, maxilla, and mandible were determined using new input data combined with published data (Cormier, 2008). Using these data, impact forces necessary to produce a 50% risk of fracture for the facial bones were calculated (Figure 9).

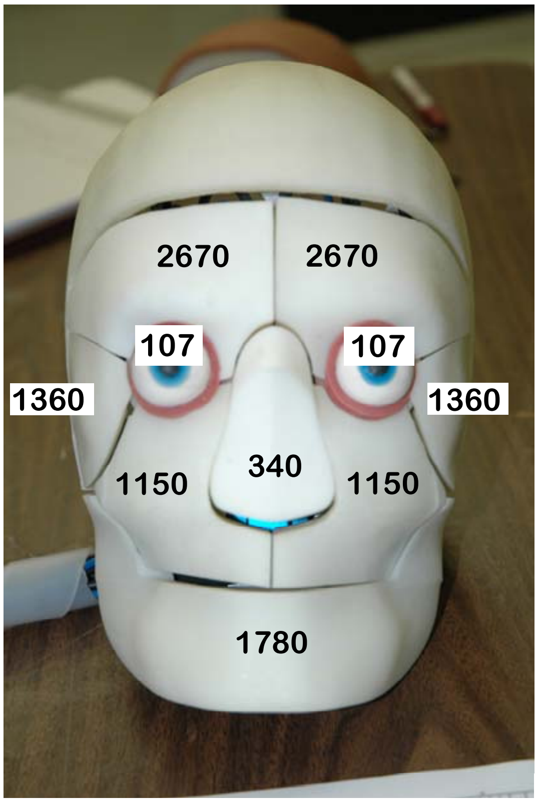

Figure 9: The FOCUS headform and the thresholds for 50% risk of fracture in Newtons.

A load of 2670 N is presented as the 50% risk of injury for the frontal bone. The Consistent Threshold (CT) method (Cormier 2008) and the thresholds for Nahum (1975), Hampson (1995), and Allsop (1988) all support 2670 N as 50% risk of fracture.

The suggested fracture load for the nasal bone is 340 N which is based on a combination of the CT analysis (Cormier 2008), the threshold from Hampson (1995) and the threshold from Nahum (1975).

A load of 1150 N is the presented 50% risk of injury data for maxilla fracture. In the case of maxilla fracture, the CT analysis for 50% risk (Cormier 2008) and the threshold from Schneider (1972) support this risk assessment.

The thresholds of previous studies along with the CT analysis for the Cormier (2008) study were used to determine the recommended 50% risk of fracture load of 1780 N for the mandible (Cormier 2008, Nahum 1975, Schneider 1972).

The suggested 50% risk of fracture for the zygoma is 1360 N and is based on the average from tests performed by Hodgson (1967) with a 6.5 cm impactor area on the zygoma.

3.3 Limitations

The FOCUS headform is more suited to testing where the projectile characteristics in terms of interaction with the eye are not known. In the circumstance where the size, velocity, and mass of an impacting object are known, it is recommended that injury risk is determined based on the specific projectile characteristics, such as those presented Kennedy *et al.* (2006). The FOCUS injury risk functions have been developed to be conservative estimates of injury risk. Future work is ongoing to create injury risk functions for corneal abrasion, hyphema, lens dislocation, and retinal damage.

Thresholds for the 50% risk of fracture from frontal blunt loading were established for five facial bones. Future testing will be performed to determine the full risk functions for each facial bone. Additionally, the current results represent frontal impacts for all tests. Lateral impacts were not included in the presented thresholds but are an area of interest in the future. Future work is ongoing to improve risk characteristics for facial fracture, provide information for lateral impacts, and increase the database of current facial fracture data.

3.4 Applications

The ability of the FOCUS headform to predict eye injuries gives it a unique capability that no current ATD headform possesses. Projectile tests can be conducted on this instrumented headform and the output will reflect the magnitude of the eye and facial impact event. This can then be equated to a risk for potential eye and facial bone injury using the given injury criteria and also can serve as a means of comparing the relative benefits of different types of protective eyewear in preventing eye injury and facial fracture.

As shown in previous research, face shields (Figure 10) decrease the facial fracture risk by distributing the load across the face (Manoogian, 2006). Results show that the maximum load decreased with the use of a countermeasure or safety glasses (Figure 11). Impact tests can be performed to determine the effectiveness of countermeasures in preventing facial fracture and globe rupture with the FOCUS headform, providing additional

information demonstrating the force distribution on the different facial bones. These data can then supply valuable information used to design improved countermeasures.

Figure 10: Custom face shield fitted to a Hybrid III 50th percentile dummy.

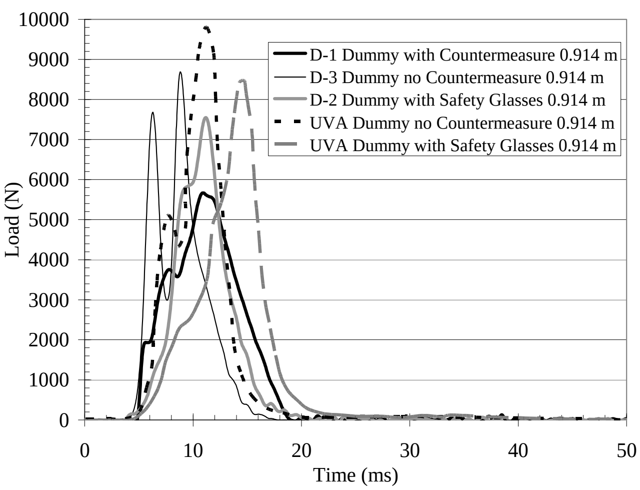

Figure 11: Impacts to the Hybrid III dummy head yielded similar results to previous tests.

4. CONCLUSION

The relative severity of both eye and facial injuries is much greater for the military than in the civilian population; however, these injuries in both the civilian and military sectors can be severely debilitating and pose an enormous health cost. The current study presents a biofidelic synthetic eye and eye injury criteria that can be used for accurate assessment of the effectiveness of goggles, face-shields, and other protective devices for preventing serious eye and facial injuries. This new capability enables the military to not only evaluate protective equipment prior to deployment, but also will be useful in the civilian population for evaluation of facial impact scenarios (e.g., sports injuries and automotive accidents). Current FOCUS projects included the first objective assessment of maxillofacial protection devices for U.S. Army aviation and ground Soldiers.

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